A MODEL FOR PREDICTING SIGNAL TRANSMISSION PERFORMANCE OF WIRELESS SENSORS IN POULTRY LAYER FACILITIES

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ABSTRACT. *Wireless sensor networking technology has great potential to advance monitoring of animal environments. Recent applications are very limited due to a lack of understanding of the performance of wireless sensors in large-scale, concentrated, and confined animal feeding operations. Wireless sensor performance in poultry layer facilities was evaluated through empirical testing of path loss, which was measured as the received signal strength indicator value, using two commercial wireless sensor modules connected in a point-to-point configuration. Significant path loss was caused by free space, animal cages, animal presence, and concrete floor separations. The influence of each affecting factor was modeled based on the single slope derivation of the Friis free space path loss model. The transmission efficiency factor within a single aisleway was found to be 2.6. Fully stocked animal cages yielded an additional 22.5 and 24.9 dB path loss for one and two cages, respectively. Concrete floors separating levels of the test layer facility exhibited an additional path loss compared to the path loss at a similar distance when not separated by concrete. A two-dimensional path loss prediction model was developed based on the log of transmission distance, the number of aisle separations, a second-order aisle separation term, and an interaction term between separation distance and aisle separation. The model was able to predict 86% of the system variability and was able to produce an average error of -0.7 dB for all combined points. The model results are based on experimental measurements made versus a 1 mW transmission source and can thus be accurately scaled to predict the performance of higher or lower power transmission systems within a similarly designed poultry layer facility.*

Keywords. *CAFO, Instrumentation, Path loss, Sensors, Wireless communication.*

Understanding the animal environment and air quality is a crucial first step in maintaining healthy and productive livestock as well as ensuring the health of employees within the agriculture sector (Arogo et al., 2003). The foremost challenge in understanding the dynamic aerial indoor environment is overcoming the large scale and high concentration of commercial confined animal feeding operations (CAFO). Research has shown that many indoor environment parameters have high temporal and spatial variability and require dense sampling methods for accurate measurements (Parbst et al., 2000). Currently, the state-of-the-art method to intensively and extensively quantify the air emission and indoor environment of animal housing is the mobile lab sampling method, in which sensors and air samplers are placed in the buildings and connected to a stationary analysis lab through lengthy cables and sampling tubing. The typical sensors include temperature, humidity, light intensity, ventilation activity, and static pressure sensors (Heber et al., 2001; Schmidt et al., 2002; Wilhelm and McKinney, 2001; Xin et al., 2003; Zahn et al., 2002; Zhao et al., 2005). Many of the individual sensor or gas acquisition lines stretch to over 125 m in length and are very difficult to relocate after their initial installation. Density of sampling point locations for many environmental parameters is typically limited by the cost and time requirements of installation as well as the limit in data acquisition capacity of the mobile lab computer system.

Increased sampling density and reduced sensor installation costs have been shown to be feasible through the use of wireless electronic sensor networks (Darr et al., 2007). Since wireless sensor networks transfer data without physical cabling, wireless sensors provide the ability to truly locate sensors without limitations of the physical environment. This has particular application in monitoring CAFO environments, where the ability to densely locate sensors within a localized zone can lead to much greater understanding of the dynamic fluctuation within the sampled area. Wireless sensor technologies also allow sensors to be easily relocated during the course of the sampling period in order to respond to changes in the building configuration or ventilation plan.

Challenges exist, though, in applying wireless sensor technology to monitoring agricultural environments. Butler et al. (2004) demonstrated the ability to apply wireless networking to livestock tracking in an open pasture environment. This approach was similar to work focused on wireless sensing of soil physical properties (Kim et al., 2006).

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On a more localized scale, wireless systems have been used to transfer animal health information over short distances (Nagl et al., 2003). Although not conducted in real time, radio-frequency identification devices have successfully monitored many physical parameters, including soil properties and erosion (Hamrita and Hoffacker, 2005; Nichols, 2004). No previous work, though, has documented the electromagnetic environment within a highly concentrated CAFO facility, which differs greatly from other monitoring environments. CAFO facilities exhibit extreme challenges in maintaining a wireless network across the entirety of an animal building due to the dense animal populations, holding cages, and structural materials, which are common in large production facilities. A sufficient model to describe the internal electromagnetic environment of a CAFO is required to design a reliable, high-performance wireless data acquisition system. Specifically, path loss information related to signal attenuation within CAFOs would allow future researchers to employ a totally wireless solution for intensive monitoring of macro- and microclimates.

The objective of this work was to quantify the electromagnetic performance of wireless sensors within a CAFO facility and to develop a predictive model that could be used to implement robust sensor networks in the future. Specific objectives include:

- Determine key distinguishing factors that cause wireless path loss within a poultry layer CAFO.
- Develop a two-dimensional signal attenuation model for predicting path loss in poultry layer CAFOs.
- Evaluate the accuracy of the two-dimensional signal attenuation model by direct comparison to a similar but physically unique test facility.

Materials and Methods

Specification and Design of a Test Fixture

A test fixture was designed to experimentally quantify the path losses within a CAFO and verify theoretical path loss models. This fixture incorporated an IEEE 802.15.4 Zigbee module (ETRX1, Telegesis, Marlow, U.K.) along with the necessary power conditioning and data acquisition circuits. This specific Zigbee module was chosen based on its commonality with other commercial wireless sensor products, small form factor, embeddable antenna, serial interface for simple data acquisition and control, and controllable transmission power. The transmission power of the ETRX1 module was adjustable from 0 to -32 dBm, but was maintained at 0 dBm throughout all tests. This transmission power level was chosen so that future use of these results would be easily transferrable and would not require link budget calculations to be corrected for non-unity transmission gains. The standard surface mount chip antenna provided a gain of -2 dBi when averaged in all directions. The receiver sensitivity was -90 dBm. The ETRX1 module was powered by a 3 V regulator and had an average current consumption of 30 mA. The functionality of the ETRX1 module is provided internally by an EM250 (Ember Corp., Boston, Mass.) single-chip Zigbee solution and is addressed through a series of product-specific AT serial commands.

In order to determine the wireless path loss between two distinct points, a pair of test fixtures was used, each containing an ETRX1 Zigbee module. One module acted as the transmitter while the other was a receiver in a point-to-point network connection. An embedded controller (Flash Core B, Tern, Inc., Davis, Cal.) was interfaced to the receiver module and was used to control the flow of wireless communication. At a 0.5 Hz interval, the embedded controller issued a command that initiated a wireless transmission between the transmitter and receiver. The receiver then reported the received signal strength indicator (RSSI) value of the transmission back to the embedded controller for permanent storage. These experiments were specifically aimed at collecting RSSI path loss information and as such did not collect any sensor data.

A keypad was used to allow the operator to enter the transmission distance between the transmitter and receiver, which was logged along with the signal strength information. RSSI is a direct measure of the strength of a received wireless signal and is represented as the ratio of power received to a 1 mW power reference. The RSSI value does not provide any indication as to the quality of the received signal nor if the signal is being transmitted from the desired source, but rather is simply a measurement of signal strength. RSSI values provide significant advantages when developing models of wireless environments because the modeling results are relative to a 1 mW transmission source; thus, the performance of higher or lower power systems can be predicted by including an offset associated with the difference in transmission power.

The test fixture (fig. 1) was fitted with an edge connector (DTM13-12PA-12PB-R008, Deutsch, Hemet, Cal.) and placed in a plastic enclosure (EEC-325X4B, Deutsch, Hemet, Cal.). The plastic enclosure asserted a limited path loss, but for long-term CAFO operations it is imperative to maintain a completely sealed wireless sensor and prevent corrosion caused by the gasses and dust present in CAFO buildings. The Zigbee internal chip antenna also provided less performance than a full whip or other high-gain antenna design, but the internal chip antenna was more representative of what would typically be used in a CAFO environment and again allowed for complete sealing within the enclosure.

Path Loss

The effectiveness of wireless sensor communication is directly related to the capacity to transmit electromagnetic radiation through the sensor environment. If the signal power received is greater than the reception sensitivity, then a successful communication link is created. The difference between the power transmitted and the power received is defined as the transmission path loss. All environments exert some level of path loss, or degradation of the radiated signal, and quantifying the level of loss from different environmental factors enables more effective designs of sensor networks in the future. The most basic wireless environment assumes that the transmitting and receiving antennas are separated in free space by a finite distance and that the antennas are within clear line-of-sight of one another. It further assumes that the antennas are isolated from any surfaces that may reflect or otherwise induce electromagnetic noise. Based on these assumptions, the Friis equation (Balanis, 2005) for line-of-sight transmission loss is:

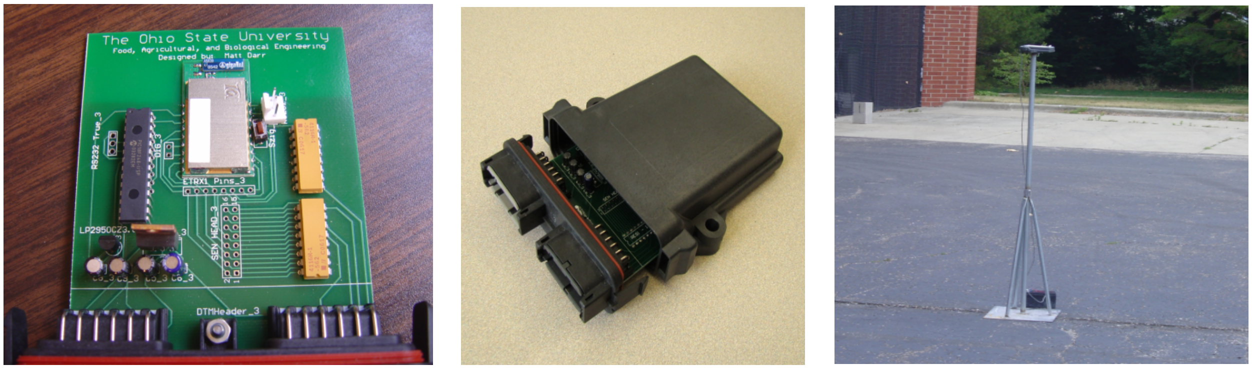

Figure 1. Left to right: ETRX1 mounted to a custom circuit board, placed within a completely sealed plastic enclosure, and mounted to a 1.5 m pole used for path loss testing.

$$P_r = G_r G_t \left(\frac{\lambda}{4\pi r} \right)^2 P_t \tag{1}$$

where
P_r = power received (mW)
P_t = power transmitted (mW)
G_r = receiving antenna gain (unitless)
G_t = transmitting antenna gain (unitless)
r = separation distance of the antennas (m)
λ = wavelength of the signal (m).

A common derivation of this power equation is to represent the power level as a ratio of power received to power transmitted and report this ratio in decibel units:

$$\frac{P_r}{P_t}(\text{dB}) = 10\log\left[\frac{G_r G_t \lambda^2}{(4\pi)^2}\right] - 20\log(r) \tag{2}$$

The first term in this equation is based strictly on the antenna gains and wavelength of the signal. This will be a constant for a particular wireless link and is independent of the environmental surroundings. The ratio of power will increase with increasing antenna gains and will decrease with increasing transmission frequency. The second term describes the path loss within a free space environment and is dependent on the separation distance between the receiver and transmitter. When free space does not exist between the receiver and transmitter, it is common to modify this equation by adding an efficiency factor to the second term. This factor will cause an increase in signal decay as it travels through a specific medium. In its reduced form, this model is referred to as the single slope model due to its simplification of parameters (Goldsmith, 2005):

$$\frac{P_r}{P_t} = 10\log\left[\frac{G_r G_t \lambda^2}{(4\pi)^2}\right] - N \cdot 10\log(r) \tag{3}$$

where N is the efficiency factor (unitless).

The efficiency factor is known to be 2 when in free space. The greater the value of N, the greater the rate of signal decay through a medium. N can be less than 2 and thus better than the free space condition when a network connection exists in an amplifying environment, such as a solid hallway that acts as a signal waveguide. Path losses will occur from many sources within CAFO buildings. There will be natural path loss related to the separation distance of the sensor nodes that can be estimated from the Friis equation. There will also be path loss caused by signal reflection, multipath reception, signal diffraction, shadowing, and signal absorption. Each of these physical path loss factors will sum to a single efficiency factor for a specific environmental condition.

If accurately known, the efficiency factors can be used to accurately predict path loss through a wireless environment and can be used to design the required transmission strength and receiver sensitivity to ensure a quality wireless transmission link.

Test Facility Selection

Although swine, bovine, and poultry CAFOs are all of major concerns regarding air quality measurement, poultry operations exhibit the most challenging environment for wireless sensing due to their high stocking density and wide use of elevated cages to hold animals. Two poultry layer barns in Ohio served as the primary test facilities for this study. These barns were belt-battery types that have been retrofitted from a high-rise facility. This provided a unique research site in which testing was possible for both typical belt-battery barns with multiple cages of animal separation and with high-rise specific parameters such as concrete floors separating multiple levels of the facility. At 120 m long and 20 m wide, each facility was representative of typically commercial-scale production (fig. 2). Each barn held nearly 250,000 layers when fully stocked and had a stocking density of 402 cm^2 per bird. Empirical models were created based on performance data collected in a single facility (barn A). The second facility (barn B) was used to confirm the empirical model results and to evaluate the variability in path loss data between buildings.

Experimental Plan and Statistical Design

Many physical factors within a CAFO will cause attenuation in wireless signals and limit the performance of wireless sensor networks. The experimental wireless attenuation results were tested through a factorial-randomized complete block with main effects as listed below. The statistical significance was 0.05 for all tests. Data were analyzed using an ANOVA in Minitab (v15.1.1.0, Minitab, Inc., State College, Pa.).

Enclosure Attenuation

The wireless test unit was fully sealed in a plastic enclosure to prevent corrosive gases and dust from contacting the circuit board components. The enclosure was constructed

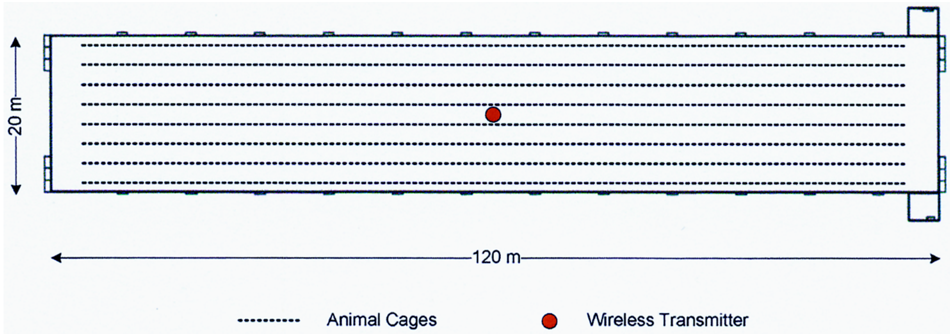

Figure 2. Dimensional diagram of barns A and B. Each facility had identical overall dimensions of 120 × 20 m. The wireless transmitter was located in the center of the barn, and experimental signal strength readings were collected by locating the wireless receiver at a specific location relative to the transmitter.

from acrylonitrile butadiene styrene (ABS) plastic and had an average wall thickness of 3 mm. Encasing the sensor caused attenuation to the wireless signal strength. The magnitude of this loss was quantified by comparing the free space path loss characteristics of the test fixture with and without the sealed enclosure when located in an open-air free space environment. The transmitter and receiver were aligned facing each other, and a series of path loss values were recorded at 3 m intervals over a range of 3 to 30 m with and without the plastic enclosure present. The average path loss with enclosures was then subtracted from the average path loss without enclosures for each measurement point to attain a direct metric of path loss from the presence of the plastic enclosure.

Separation Distance

The separation distance between two wireless sensors caused a path loss as defined by the Friis equation. An efficiency factor needed to be quantified to accurately predict the impact of separation distance within a single aisle of a poultry facility, which was very different from a standard open-air condition. The path loss between the transmitter and receiver was measured from 0 to 60 m with a sampling resolution of 1.4 m. The antennas on the transmitter and receiver were both maintained planar to each other and were oriented in the reference plane horizontal to the circuit board.

Cage Separation

Animal cages exerted a path loss associated with the reflection and multipath signal interference. Tests were conducted to quantify the cage separation efficiency factor by evaluating the RSSI between a transmitter and a receiver separated by 0, 1, and 2 rows of empty cages. Each cage separation represented a new mode of path loss. A test procedure was developed to accurately quantify the path loss caused by wireless transmission through an animal cage. This test was conducted by aligning the transmitter and receiver directly across from each other under a known cage separation. Data were collected over a range of 30 m within the layer house, with the transmitter and receiver being located directly across a single cage for each measurement point. By moving both elements, the impact of cage separation and the variability in path loss over different portions of the building were quantified. The cages used for this study were standard layer cages measuring 1.2 m wide and 3.0 m tall. Each row of cages held five tiers of birds. The height of the sensors was maintained constant at 1.5 m.

Animal Absorption

Cage separation testing was repeated with fully stocked animal cages to quantify the amount of path loss associated directly with the presence of the animals. The fully stocked condition was represented as a stocking density of 402 cm^2 per bird. Once mature, layer birds reach a uniform size and maintain that size throughout the majority of their productive life. Based on this fact, bird size was not a test factor within the scope of this study. Each barn was stocked with mature Lohman birds from the M74 strain. A direct comparison of the results between full density and no animal density yielded the animal absorption effect.

Concrete Separation

Barn A had a concrete floor structure that separated the upper and lower levels. This is a typical design for many high-rise or retrofitted belt-battery layer barns. Concrete is widely known to cause significant wireless signal attenuation, but is also known to have great variation in its attenuation impact. Depending on the formulation of the concrete, the thickness of the concrete, and the amount of reinforcement steel used, the attenuation levels varies greatly. In the barns studied for this project, no steel reinforcement was included, but the concrete was installed in a modular way and had a varying cross-section across the width of the buildings. The modular concrete was formed into a C-channel shape with a width of 0.91 m (36 in.), a center thickness of 0.25 m (10 in.), and an edge thickness of 0.46 m (18 in.). To quantify the efficiency factor associated with a concrete structural divide between the upper and lower levels of the layer house, the separation distance tests were repeated with the transmitter on the upper building level and the receiver on the lower building level. The performance was quantified by direct comparison of path loss for single-level and concrete-divided tests.

Determination of Sampling Size

The sampling size of the path loss data was designed to maintain the confidence interval of the measurements within an acceptable range of ±1.5 dB. High RSSI variance was expected due to fast fading of wireless signals within the CAFO environment. A preliminary study of the temporal distribution of RSSI values within a CAFO was conducted, and the results provided an estimate of the standard deviation of RSSI values. The transmitter and receiver were located in barn A with one aisle separation and 8 m of linear distance separation. After a total of 2,663 RSSI samples, the data were analyzed and produced a standard deviation of 3.9 dB. This standard deviation value was significantly higher than the 1.1 dB value recorded with a similar separation distance in an open-air environment.

The higher variability in signal strength under static measurement conditions indicated that the environment does in fact induce fast fading and multipath errors. The source of multipath interference was the summation of wave components in a multi-ray field. As the wireless signal radiates from the transmitter source, some of the energy travels directly to the receiver through small line or sight paths. Other components of the transmitted energy reflect off the many surfaces of the CAFO and cause fading or attenuation of the direct signal. The magnitude of fading was not constant, but rather random and dependent on the individual reflection of each signal. This randomness resulted in higher variability in the signal strength measurement between two points with strong fading characteristics. Other types of path loss, such as absorption or total reflection, continuously impacted the magnitude of signal strength rather than affecting the variation between sequential measurements and thus will not impact the fast fading component of the signal.

Based on the signal variance tests, a sampling point scheme was designed to maintain the uncertainty of measurement less than ±1.5 dB. The true standard deviation for the data was assumed to be the value returned from the preliminary test. By applying this result along with a 95% confidence band of ±1.5 dB, the minimum required sample size was 27 measurements per test point. To ensure a factor of safety regarding the prediction of the standard deviation, a sample size of 30 signal points was chosen as the desired size for all path loss evaluation trials.

Results and Discussion

Impact of Plastic Enclosure on Signal Strength

The sealed housing that contained the Zigbee test fixture prevented the sensor circuit board from being exposed to potentially high levels of ammonia and hydrogen sulfide in the CAFO, which can cause corrosion on the circuit board. Although beneficial to protecting the integrity of the circuit, the enclosure asserted an immediate source of path loss. Most plastic materials have a relative dielectric constant of 2 to 3, indicating that they are 2 to 3 times less able to allow electromagnetic energy transmission. On a decibel scale, this negative gain will represent an increased path loss of 3 to 4.8 dB depending on the exact material makeup of the enclosure. Experimental results indicated a mean path loss of 3.5 dB associated with the plastic enclosures. The 95% confidence interval for this mean spanned from 2.1 to 4.8 dB. The mean value of 3.5 dB fell well within the predicted range of 3 to 4.8 dB for plastics.

Impact of Linear Distance on Signal Strength

Comparison of the results from the three test repetitions of the impact of linear distance within an aisleway on path loss found that they were all statistically similar at the 95% significance level. These results were then combined into a single slope regression function by calculating the logarithmic transmission distance and averaging the regression fits at each 1.4 m sampling interval. The output of the averaged regression models between the logarithmic transmission distance and the path loss yielded an offset of -41.2 dB and a slope of -25.7 (eq. 3, fig. 3). This resulted in an N value of 2.57. The offset of -41.2 dB was very close to calculated theoretical offset of -44.2 dB based on a signal wavelength of 0.1223 m and antenna gains of -2 dB at the receiver and transmitter. The antenna gain was estimated as the average gain over all transmission angles and was most likely the cause of variation between the theoretical and experimental offset values. An N value greater than 2 indicated that the path loss within a single aisle in a poultry layer facility was greater than the path loss experienced in an open-air environment. It also confirmed that the cages do not act as a signal waveguide.

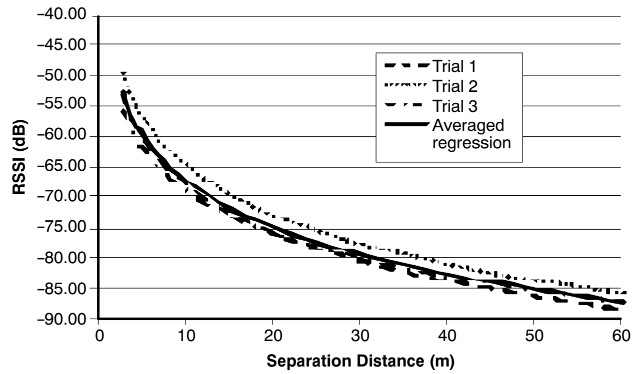

Figure 3. Cumulative regression results for average of three test repetitions to predict path loss through a single aisleway in a poultry layer facility.

Impact of Animal Cages on Signal Strength

Experimental results indicated that the average path loss across a single, fully stocked cage was -72.7 dB with a 95% confidence interval width of only 0.83 dB (fig. 4). The linear distance across the width of the cage and between the transmitter and receiver during this test was 2.26 m. The predicted free space path loss for a separation distance of 2.26 m was -50.2 dB based on experimental measurements at this distance. The difference between the test condition with a fully stocked cage and the baseline condition of no cages yielded a -22.5 dB path loss difference associated with a single cage.

These results were compared to an experimental test conducted in a facility with an identical set of cages but with no animals present. For this test, the average path loss was found to be -60.9 dB (fig. 5). The difference between this observation and a fully stocked cage was a -11.8 dB path loss directly caused by the presence of animals in the cage. This was a very significant value, but was not unexpected given the tight stocking density of caged layer birds and the low conductivity of biological tissues in the 2.4 GHz frequency range (Gabriel et al., 1996).

This comparison test was repeated for cages with and without birds for two cage aisles of separation. Results showed the empty facility to have a two-cage path loss of -74.8 dB, while the fully stocked facility had a path loss of -82.8 dB. This was in comparison to the predicted path loss of -57.9 dB for a similar transmission distance in free air. Less significance was seen from the animals because of the larger impact of multiple cage rows. The stocked cages yielded a 24.9 dB loss, while the empty cages yielded a 16.9 dB loss. The loss associated with birds was then calculated as 8.0 dB for a two-cage system.

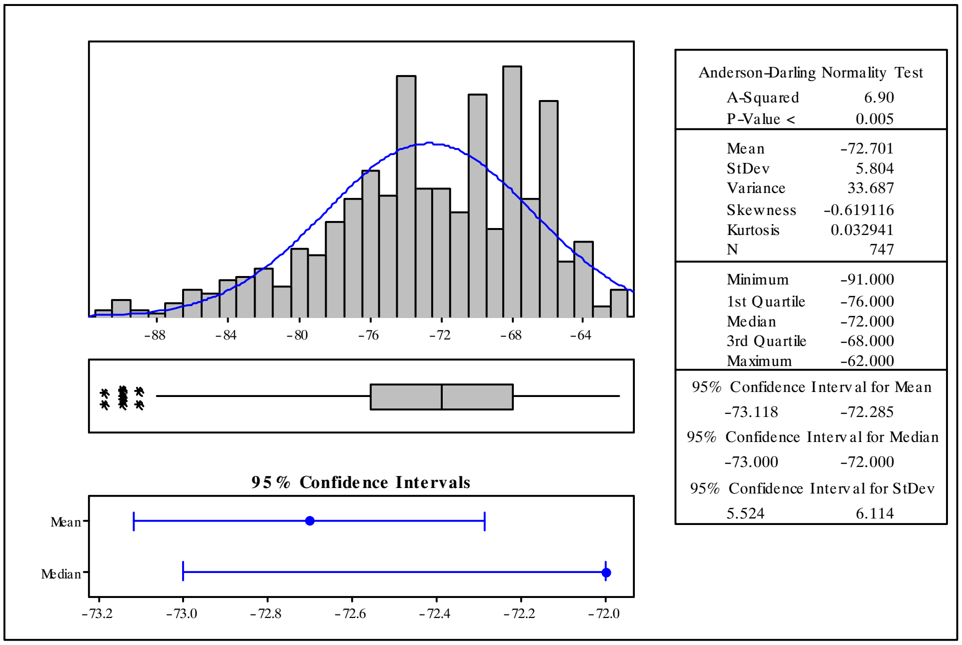

Figure 4. Interval plot and statistical summary of RSSI values for repeated measurements across a single fully stocked cage.

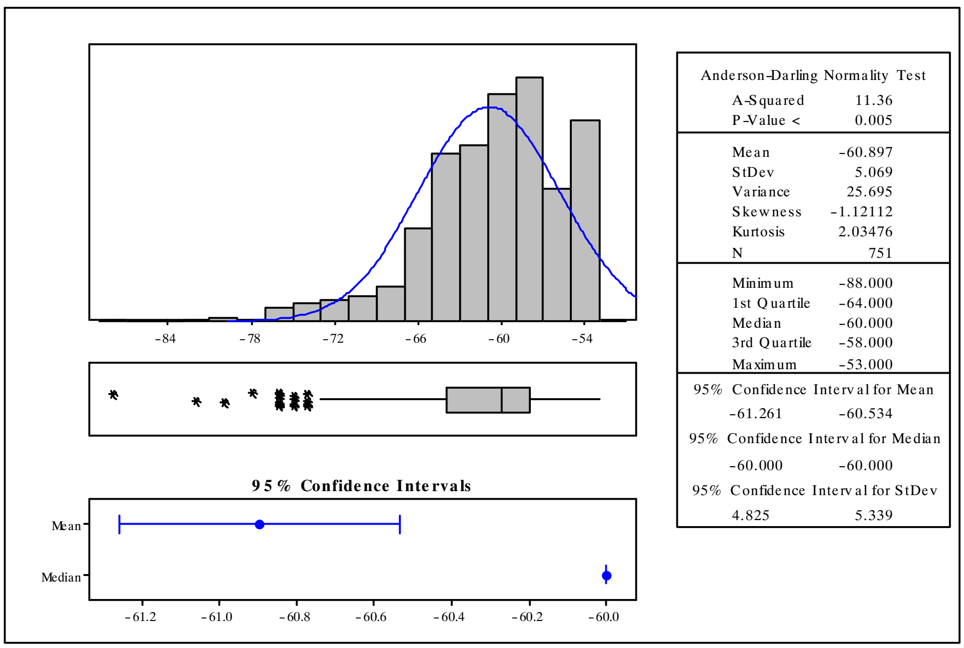

Figure 5. Interval plot and statistical summary of path loss values for repeated measurements across a single empty cage.

Impact of Concrete Floor on Signal Strength

To study the affect of concrete floors on wireless signal attenuation, a wireless transmitter was placed on the upper level of the CAFO building and a receiver was placed on the lower level. Tests to monitor the effect of separation distance were conducted. Results showed significant levels of attenuation caused by the concrete separation (fig. 6).

A comparison of the regression models for concrete separation versus no concrete reveals an additional atten-uation of -22.97 + 10.57 log(r) associated with the pre-sence of concrete. This was significant when compared to other modes of attenuation and will severely limit the expansion of wireless networks in multilevel buildings. Furthermore, due to the non-constant cross-sectional structure of the concrete, the variability in the concrete path loss was greater. This can be quantified by comparing the R^2 value of 0.78 for path loss within an aisleway to the R^2 value of 0.61 for path loss through concrete, where R^2 represents the proportion of variability in the data that is accounted for by the statistical model.

A 2D Signal Attenuation Model of Signal Strength in a Poultry Layer Facility

Spatial Distribution of Signal Strength

A two-dimensional survey of signal strength was conducted by placing a stationary transmitter in the center of a fully stocked poultry belt-battery layer house (fig. 7). The receiver was moved at 1.4 m increments away from the transmitter, and

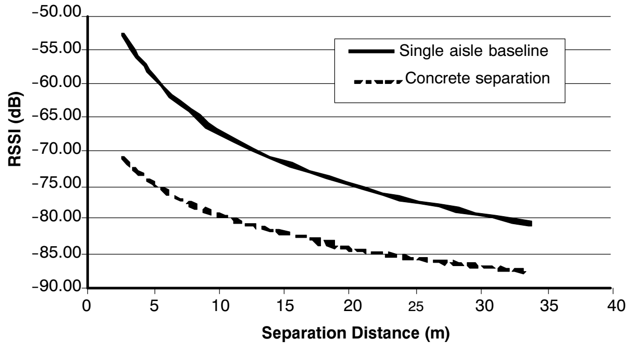

Figure 6. Comparison plot of path loss in one aisleway with and without a concrete structural separation of the transmitter and receiver.

30 RSSI measurements were taken at each point. This was repeated for 0, 1, 2, and 3 cage aisle separations. The previous analysis of cage separation only tested 0, 1, and 2 cage aisle separations because the results at 3 cage separations were very near the lower measurement limit and would bias a comparison of stocked and empty cages. The third cage aisle separation was included though in this two-dimensional analysis to fully describe the boundary condition at this extreme case. A correlation analysis indicated that both the aisle separation and the log of the transmission distance were statistically significant in predicting the path loss value. A regression analysis was conducted to relate the signal strength throughout the building to these parameters (eq. 4).

$$\mathrm{RSSI} = -46.0 - 0.713A_s - 17.5\log_{10}(r) \quad (4)$$

where

RSSI = estimated signal strength (dB)

A_s = number of aisle separations

r = separation distance of the antennas (m).

The regression analysis yielded an R^2 value of 0.68 for predicting the path loss based on aisle separation and the log of the transmission distance. The remaining 32% of variations were due to other factors not included in the prediction parameters and random variation caused by localized fast fading within the physical layout of the barn. The p-values were less than 0.000 for both regression factors, indicating a high level of significance in the factors for offset, row separation, and log of separation distance.

A scatterplot of the model residuals versus transmission distance showed the residuals to be evenly distributed around zero, indicating that the chosen model was appropriate. The scatterplot of residuals versus row separation showed signs of non-normality, as the residuals were not normally distributed around a mean residual of zero. This result can be expected based on the prior results of signal attenuation through cages. In order to correct for the non-normality associated with path loss across aisles and to improve the overall relationship between path loss and the spatial location of sensors, the regression analysis was modified to include a second-order aisle loss term as well as an interaction term between aisle separation and the log of the separation distance.

$$\mathrm{RSSI} = -45.2 - 25.2A_s + 4.19{A_s}^2 - 23.7\log_{10}(r) + 6.58A_s\log_{10}(r) \quad (5)$$

These additional model predictors increased the R^2 value to 0.86 (fig. 8) and reduced the confidence interval of the residuals (fig. 9). Furthermore, the p-value for all model terms was less than 0.000, which indicates that all factors are significant at a level less than the tested value of 0.05. This confirmed the previous hypothesis that there was a visual interaction between the aisle separation and the log of distance. The confidence interval for the residuals was now reduced to ±0.741, and a new matrix plot of response and predictor variables did not yield any additional concerns regarding non-normality or variable interaction.

Verification of 2D Signal Attenuation Model by Comparison to Second Test Building

A full sight survey was also performed in barn B, which was physically identical to barn A (fig. 10). Attenuation data for separation distance and cage separation were used to evaluate the accuracy of the path loss predictor model and analyze its ability to predict performance for a building with no prior test data. The experimental data were compared to the model data, and error values were established across both transmission distance and cage separation. The 95% confidence interval for model error produced a range of

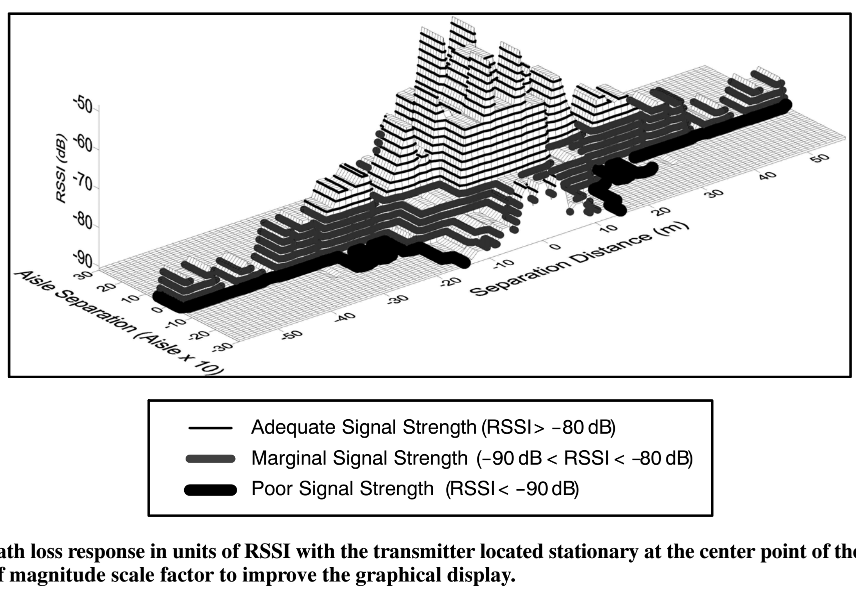

Figure 7. Barn A actual path loss response in units of RSSI with the transmitter located stationary at the center point of the building. Aisle separation is plotted with an order of magnitude scale factor to improve the graphical display.

Regression Analysis: B3 RSSI versus Log Distance, Aisle Separation, Aisle Separation^2, and Aisle-Log Distance Interaction

Regression equation: $\text{B3 RSSI} = -45.2 - 25.2\,A_s + 4.19\,A_s^2 - 23.7\,\text{Log}(r) + 6.58\,A_s \times \text{Log}(r)$

Predictor	Coef	SE Coef	T	P
Constant	-45.151	1.947	-23.19	0.000
A_s	-25.153	1.891	-13.30	0.000
A_s^2	4.1909	0.4302	9.74	0.000
Log(r)	-23.729	1.444	-16.44	0.000
A_s x Log(r)	6.582	1.085	6.07	0.000
S = 3.461	R^2 = 86.7%	R_{adj}^2 = 86.0%		

Figure 8. Regression analysis results for 2D spatial model with second-order aisle term and interaction term included.

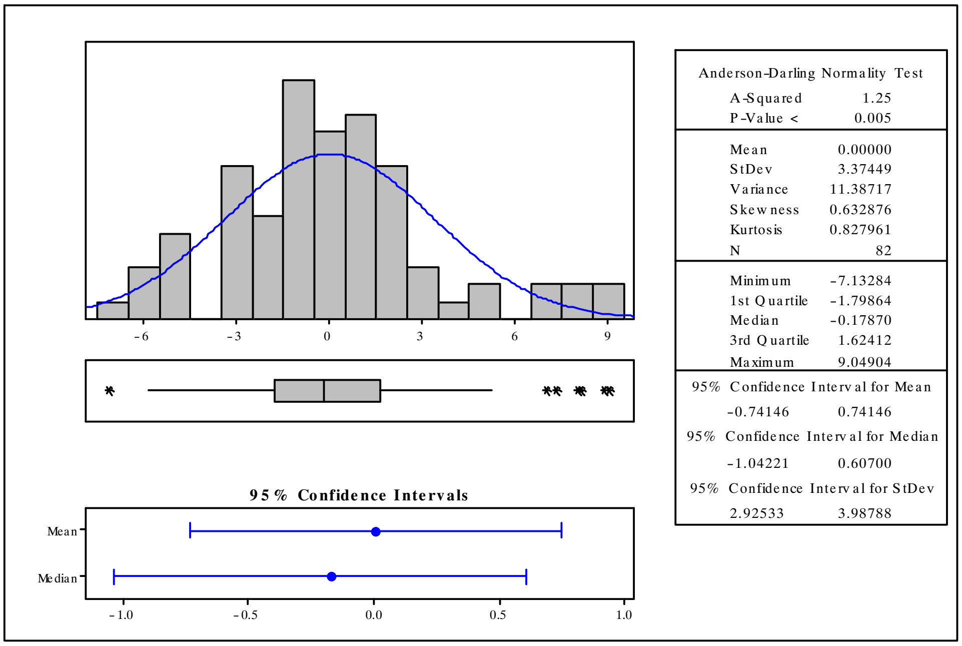

Figure 9. Summary of residuals for barn A path loss model after including a second-order aisle term and an interaction term for the log of separation distance and aisle separation distance.

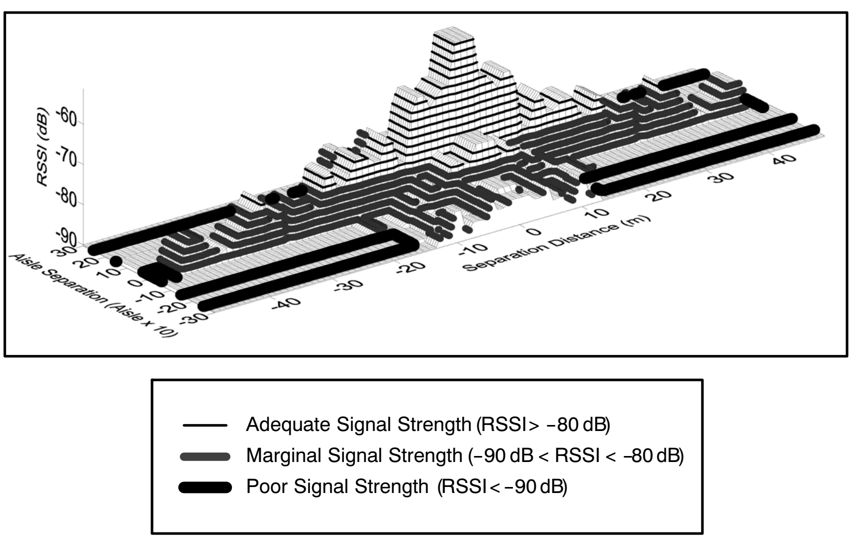

Figure 10. Barn B actual path loss response when measured with a stationary transmitter located in the center of the building and a movable receiver used to measure path loss in units of RSSI. Aisle separation is plotted with an order of magnitude scale factor to improve the graphical display.

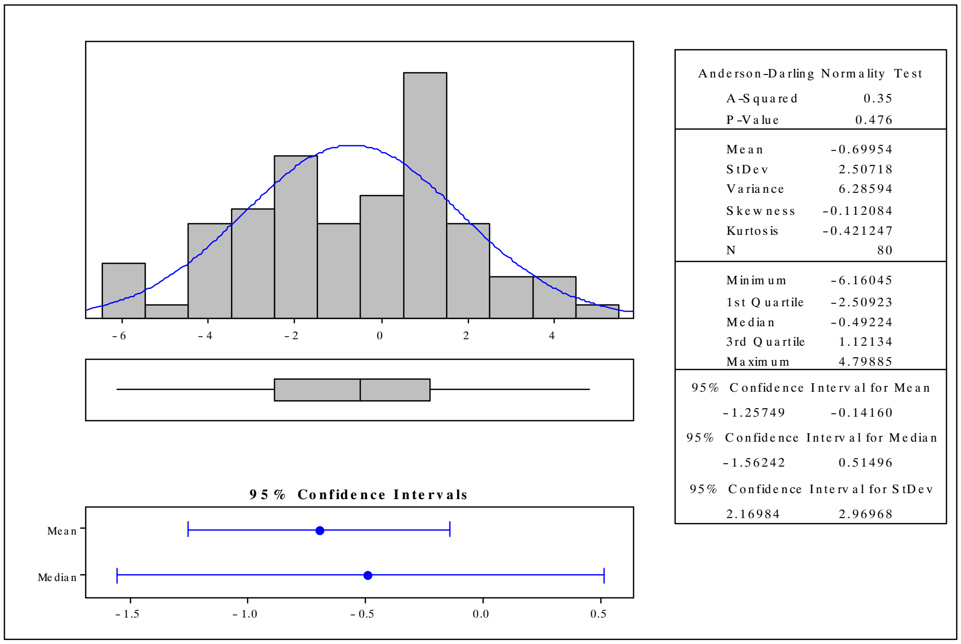

Figure 11. Statistical summary of error in estimation of barn B RSSI values from a predictor model developed based on a barn A dataset.

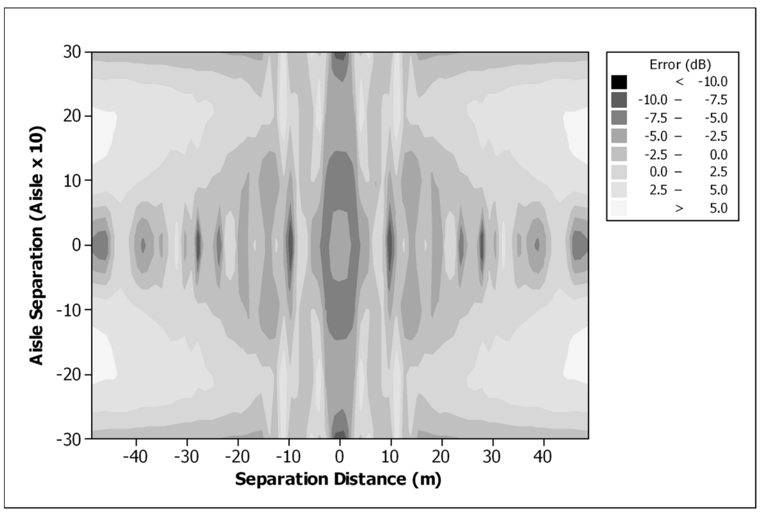

Figure 12. Contour plot of error between barn B actual path loss and predicted path loss based on the final predictor model.

(-1.25, -0.14) dB with a mean error of -0.7 dB (fig. 11). This indicated that the signal attenuation within the second test facility was on average 0.7 dB greater than the model predicted.

A comparative investigation of the response and predictor variables highlighted several key areas of interest. First, the error in predicting the response of barn B was not randomly distributed versus the aisle separation or the distance. This result was indicative of the reduced accuracy in the prediction model at the extreme dimensions of the model where an asymptotic response exists. The prediction model also tended to underestimate path loss in very low path loss zones and overestimate path loss in very high path loss zones.

Errors associated with the prediction model tended to oscillate between positive and negative values (fig. 12). This response was due to differences between the smoothed predictive model and the highly variable true response, which included additional uncertainty caused by fast fading.

Overall, though, the predictive model adequately predicted the path loss of a two-dimensional poultry layer facility with a mean error level of less than -0.7 dB. This error was within acceptable design limits and has verified that the model can be used for optimization of wireless node placement within a CAFO of similar configuration.

For wireless networks to accurately communicate between individual points, a sufficient combination of signal strength, antenna gain, and path loss must exist. This model allows one parameter, path loss, to be accurately known between two potential sensor locations in a poultry layer facility. With this value known, the transmission power and antenna gains can be sized appropriately to maintain the overall system power above the receiver sensitivity level. This will guarantee a reliable data link while minimizing the overall power consumption and antenna gain. High-gain antennas exhibit some level of directionality, so by minimizing the antenna gain the design also incorporates the highest level of isotropic characteristics.

For multi-hop networks to expand over the entirety of a CAFO facility, a critical path between a backbone of nodes must exist to allow communication throughout the facility. Once established, individual nodes may be placed at any location within communication range of at least a single main node. The overall reliability of the network will be governed by an individual node's ability to route messages back to a single network sink or data logger. Low temporal variability in path loss will help encourage mesh networking within CAFOs, but individual designs will still need to specify the maximum path loss acceptable between nodes. The absolute maximum value can be established based on the antenna gain, transmission power, and receiver sensitivity characteristics of individual nodes. In addition, a factor of safety should be added to account for changes in antenna efficiency caused by dust buildup on the enclosure surface or other sources of yet unknown path loss.

Limitations of Two-Dimensional Path Loss Model

Although the two-dimensional model provided an excellent means to predict path loss within a CAFO poultry layer facility and was verified through a comparison with a second representative site, several application limitations exist for extended use of this model. First, this model was created under the maximum operating conditions of 60 m transmission distances and three aisles of cage separation. Serious prediction errors can occur if the model is applied outside of these bounds. Arguments could be made that the transmission distance could be extended based on the fundamental understanding of path loss in free space, but the same cannot be said with regards to the cage separation terms. Specifically, the second-order cage separation term cannot under any circumstance be used outside the maximum bounds of three cages. If applied outside these limits, the second-order term will increase and cause an overall reduction in path loss as the number of cages increases. This of course is not realistically possible and is simply a sign of the firm application limits of this work. Furthermore, this work was based on data collected from 2.4 GHz radio transceivers and should only be used to design other systems utilizing the same frequency band. Nearly isotropic antennas were used in this development, and the model provides no means to respond to changes in antenna characteristics such as increased gains through directional focusing of the antenna output.

CONCLUSIONS

The results of this work provide the first documentation of path loss and wireless signal attenuation within large-scale poultry layer facilities. The application of this work will lead to the development and deployment of advanced sensor networks to improve the quality, density, distribution, and flexibility of data acquisition systems in these environments. These advanced networks will then enable widespread environment monitoring on a scale currently not feasible and will enhance researchers' ability to understand and model the dynamics of CAFO environments.

It was found that building-related parameters, namely transmission distance, cage separation, concrete separation, and animal presence, all exhibited significant levels of attenuation impact. It was also shown that for caged layer poultry facilities, a two-dimensional model could be applied to predict path loss within a building environment with only two factors: transmission distance and cage separation. Model improvements were achieved by including first-order terms for transmission distance and cage separation as well as a second-order term for cage separation and an interaction term for both first-order variables. The final model provided an R^2 value of 86.7%. Comparisons of the model to experimental results in similarly designed buildings resulted in average attenuation estimate errors of -0.7 dB. Fast fading was also shown to be a major factor in attenuating wireless signals and will require a significant factor of safety in future designs to ensure transmission accuracy.

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